Draft version October 8, 2008
Preprint typeset using LaTeX style emulateapj v. 10/09/06

VLT DETECTION OF A RED SUPERGIANT PROGENITOR OF THE TYPE IIP SUPERNOVA 2008BK

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Draft version October 8, 2008

ABSTRACT

We report the identification of a source coincident with the position of the nearby type II-P supernova (SN) 2008bk in high quality optical and near-infrared pre-explosion images from the ESO Very Large Telescope (VLT). The SN position in the optical and near-infrared pre-explosion images is identified to within about ±70 and ±40 mas, respectively, using post-explosion $K_{\rm s}$-band images obtained with the NAOS CONICA adaptive optics system on the VLT. The pre-explosion source detected in four different bands is precisely coincident with SN 2008bk and is consistent with being dominated by a single point source. We determine the nature of the point source using the STARS stellar evolutionary models and find that its colours and luminosity are consistent with the source being a red supergiant progenitor of SN 2008bk with an initial mass of 8.5±1.0 $M_{\odot}$.

Subject headings: stars: evolution – supernovae: general – supernovae: individual(SN 2008bk)

1. INTRODUCTION

The red supergiant progenitors of several type II-P supernovae (SNe) have now been directly identified in pre-explosion observations. All these are moderate mass red supergiants in the range ∼7-16 $M_{\odot}$ (Smartt et al. 2004; Van Dyk, Li & Filippenko 2003; Maund & Smartt 2005; Maund, Smartt & Danziger 2005; Hendry et al. 2006; Li et al. 2006, Li et al. 2007). Recently, Smartt et al. (2008) have presented a volume limited systematic study of the progenitors of 20 type II-P SNe with high-quality pre-explosion images available. They find a minimum initial mass of $8.5^{+1}_{-1.5}$ $M_{\odot}$ for the progenitors and suggest that there is a 'red supergiant problem' with the red supergiant progenitors more massive than ∼17 $M_{\odot}$ remaining undetected.

In this letter we report the identification of the progenitor of the type II-P event, SN 2008bk, making use of adaptive optics (AO) assisted target of opportunity (ToO) observations of the SN using the ESO Very Large Telescope (VLT). SN 2008bk was discovered by Monard (2008) on 2008 Mar. 25.14 UT in a nearby (3.9 Mpc, Karachentsev et al. 2003) Scd-type galaxy NGC 7793. Li et al. (2008) obtained a more precise position for the SN which is 9".2 east and 126".4 north of the host galaxy nucleus. It was spectroscopically classified by Morrell and Stritzinger (2008) as a type II-P similar to SN 1999em at 36 days after explosion on 2008 Apr. 12.4 UT. This classification is also supported by amateur photometry[6] showing a very flat plateau, consistent with a normal type II-P SN. NGC 7793 has a wealth of pre-discovery images available and based on their astrometry, Li et al. (2008) identified a possible progenitor star in an archival I-band image from VLT/FORS. Subsequently Maoz and Mannucci (2008) estimated the J and $K_{\rm s}$ magnitudes for the progenitor from archival near infra-red (NIR) pre-explosion images from VLT/ISAAC. Using accurate relative astrometry between our high-resolution post-explosion AO images and the pre-explosion images from the VLT we show that the possible progenitor identified by Li et al. and Mannucci & Maoz is precisely coincident with the position of SN 2008bk and characterise its properties using stellar evolutionary models.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. *Observations and data reductions*

The pre- and post-explosion observations of SN 2008bk analysed in this study are summarised in Table 1. We obtained high quality pre-explosion imaging of the SN 2008bk site from the ESO Science Archive. The optical observations were taken with FORS1 (0.20″/pixel) on UT3 and the NIR observations with ISAAC (0.148″/pixel) on UT1 and HAWK-I (0.1064″/pixel) on UT4 of the VLT. The optical frames were bias-subtracted and flat fielded in IRAF. Zero point magnitudes were obtained using standard stars in the fields of Mark A, SA 110-362 and PG 1657+078 (Landolt 1992) observed during the same night as the site of SN 2008bk. For this we adopted average colour terms and extinction coefficients from Patat (2003). The ISAAC and HAWK-I frames were sky subtracted using sky frames created from the on-source exposures with the IRAF XDIMSUM package, de-dithered using centroid coordinates of a bright field star visible in all the frames and median-combined. For the ISAAC J and $K_{\rm s}$-band images zero point magnitudes were obtained using the standards FS1, FS6, FS10, FS32 and FS114 (Leggett et al. 2006) observed before and after the SN site on the same night of observation. Average ESO extinction coefficients were adopted and no colour term corrections were applied. For both FORS1 and ISAAC data the average of the zero points obtained from the different standard fields was adopted with their standard deviation as the uncertainty. The calibration was also checked against three bright 2MASS stars which gave the same results within 0.05 mag. The SN site was only covered in two

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[6] http://www.astrosurf.com/snweb2/2008/08bk/08bkMeas.htm

TABLE 1
PRE- AND POST-EXPLOSION OBSERVATIONS OF SN 2008BK SITE.

Date (UT)	Instrument	Filter	Exp. Time	FWHM
	Pre-explosion			
2001 Sept 16.0	FORS1	B	300s	1.2″
2001 Sept 16.0	FORS1	V	300s	1.0″
2001 Sept 16.0	FORS1	I	480s	0.9″
2005 Apr 21.6	ISAAC	J	17×60s	0.5″
2005 Oct 17.1	ISAAC	K_s	58×60s	0.4″
2007 Oct 16.1	HAWKI	H	2×60s	0.8″
	Post-explosion			
2008 May 19.4	NACO	K_s	20×69s	0.1″

TABLE 2
ASTROMETRY OF POST- AND PRE-EXPLOSION IMAGES.

	I	J	K_s
Error in progenitor position (mas)	49/28	2/7	2/4
Error in SN position (mas)	1/1	1/1	1/1
Geometric transformation (mas)	50/57	40/40	23/24
Total error (mas)	70/64	40/41	23/24
Difference in position (mas)	66/30	13/23	6/12

The total error has been obtained as a quadrature sum of the position errors and the geometric transformation RMS.

jittered HAWK-I H-band frames which were combined together. For the HAWK-I image the zero point magnitude and its uncertainty were obtained using five 2MASS stars within the image field.

SN 2008bk was observed with VLT/NACO (Rousset et al. 2003) using Target of Opportunity (ToO) observations as a part of program 081.D-0279 (PI: S. Mattila) on 2008 May 19.4 (UT). The imaging was carried out in the K_S-band with the S27 camera (0.027″/pixel) using the fixed sky offset imaging sequence. The AO correction was performed using the visual wavefront sensor with the SN ($m_V \sim 13$) itself as a natural guide star. The NACO data were reduced using IRAF. The jittered offset frames were median combined to form a sky frame, the sky subtracted images de-dithered making use of the centroid coordinates of the SN, and the de-dithered frames median combined. The final reduced image is of very high quality showing near-diffraction limited resolution of ∼0.1″ for the SN (see Fig. 1).

2.2. *Relative astrometry*

To precisely determine the SN position on the pre-explosion images we derived a geometric transformation between the pre- and post-explosion images. Centroid positions of 26 and 30 point sources were measured in the pre-explosion J- and K_s-band frames, respectively, and in the post-explosion K_s-band frame. The IRAF GEOMAP task was used to derive a general geometric transformation between the frames. The identification of a sufficient number of stars common between the pre- and post-explosion observations in other bands was not possible. Instead, we used centroid positions of 19 stars to derive a general geometric transformation between the I and J band images. The B and V band images were then transformed to the I-band image with simple 'rscale' transformations (incl. x and y shifts and a common scale factor and rotation for x and y) using centroid positions of 10 stars common between the frames. A transformation was also derived between the pre-explosion H and K_s-band images. The RMS values of the transformations were adopted as the uncertainties (Table 2).

The average of the positions measured for the SN using four different methods (centroid, gauss and ofilter within the IRAF APPHOT package and PSF fitting with SNOOPY[7]) was then transformed to each pre-explosion image. A point-like source is clearly visible at the SN location in the I, J, H and K_s-band pre-explosion images. In Fig. 1, subsections of the I, J, and K_s band pre-explosion images are shown together with the post-explosion image, all centered on the SN position. However, in the B and V bands no source was detected at the SN position. To confirm the coincidence of the pre-explosion source with the SN, its position was measured with the four different methods also used for the SN. The average of the measurements was then adopted as the source position and the standard deviation as its uncertainty. In Table 2, the difference between the source and SN positions in I, J and K_s-bands are compared with the total error budget in the relative astrometry (in x/y coordinates). This confirms that the pre-explosion source is coincident with the SN position within the 1σ uncertainties in both optical and NIR images.

2.3. *Photometry in pre-explosion images*

We used the PSF fitting package SNOOPY to measure the magnitude and coordinates for the pre-explosion source in I, J, H and K_s-bands. For this several suitable stars were selected to build the model PSF. Prior to the actual PSF fitting a polynomial surface was fitted to a background region centered on the source position (but excluding the innermost region around the source) and subtracted from the image. In the I-, J- and H-band residual images (with the PSF subtracted) there was little sign of the original point source, therefore confirming that the pre-explosion object is indeed consistent with a single point source in these bands. However, in K_s-band there was a faint source left in the residual image about 0.5″ south of the determined SN position. This source is at ∼10% level of the original pre-explosion source peak counts and is therefore not likely to increase significantly the uncertainties in our K_s-band photometry. The code was run both with the source position fixed (to the SN position) and free with very little difference in the measured magnitudes. The uncertainties in the measurements were estimated by simulating and PSF fitting (one at the time) nine artificial objects around the source position in the residual images. The quadrature sum of the standard deviation of the simulated source PSF magnitudes and the uncertainty in the photometric zero point magnitude was adopted as the photometric error in each band. The magnitude corresponding to a source with a flux three times the standard deviation flux found by simulating and PSF fitting faint artificial objects around the SN position was adopted as the upper limit in B and I bands. This yielded the following magnitudes for the pre-explosion source: $m(B) > 22.9$ (3σ), $m(V) > 23.0$ (3σ), $m(I) = 21.20 \pm 0.19$, $m(J) = 19.50 \pm 0.06$, $m(H) = 18.78 \pm 0.11$, and $m(K) = 18.34 \pm 0.07$.

[7] SNOOPY, originally presented in Patat (1996), has been implemented in IRAF by E. Cappellaro. The package is based on DAOPHOT, but optimised for SN magnitude measurements.

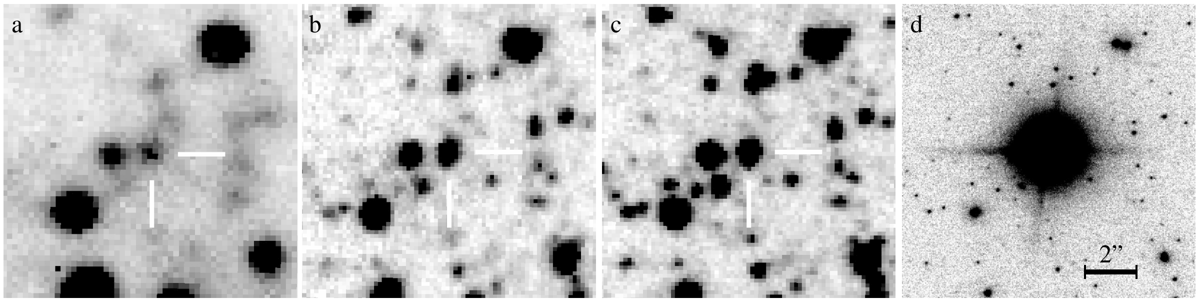

FIG. 1.— Pre- and post-explosion images (11″× 11″) of SN 2008bk site. Each panel is centered on the SN position and oriented such that North is up and East is to the left. (a) Pre-explosion VLT/FORS1 *I*-band image, (b) pre-explosion VLT/ISAAC *J*-band image, (c) pre-explosion VLT/ISAAC K_s-band image, (d) post-explosion VLT/NACO K_s-band image observed with AO. A point-like source coincident with the SN position (marked with ticks) is clearly visible in all the three pre-explosion frames. The K_s-band source is likely a blend between the progenitor and a fainter source $\sim 0.5''$ south making the pre-explosion source appear slightly elongated compared to stellar PSF in this band (see Sect. 2.3).

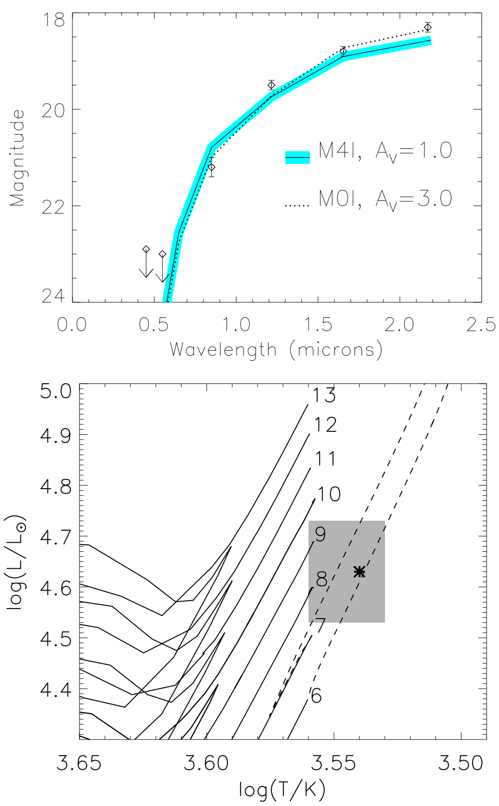

FIG. 2.— *Upper panel:* The observed SED (open diamonds) of the progenitor matching the reddened colours ($A_V = 1$) of an M4I star (LMC colours) from Elias et al (1985). The thick grey area has a width of $\pm 0.1^m$, to illustrate the range in observed colours of M4I stars in each band. This band fits the observed SED, with a small discrepancy seen in the *K*-band. An earlier M0I spectral type with a an extinction of $A_V = 3$ gives also a reasonable fit. *Lower panel:* Hertzsprung-Russel (HR) diagrams showing the STARS models for initial stellar masses between 6 and 13 M$_\odot$. The 6 and 7 M$_\odot$ model tracks during the second dredge-up phase are indicated by dashed lines. The observed progenitor luminosity and temperature are indicated by a star and their uncertainties as a shaded square.

3. THE PROGENITOR OF SN 2008BK

The SN 2008bk host galaxy NGC 7793 has two similar distance estimates of 3.91 ± 0.41 Mpc (Karachentsev et al. 2003) determined from the tip of the red giant branch and 4.1 Mpc from the Tully Fisher relation reported in HyperLEDA[8]. Here, we adopt the former as the more reliable estimate to be used in this study. The metallicity at the SN 2008bk position was determined using the relationship of Pilyugin et al. (2004) for NGC 7793. The offset of SN 2008bk from the host galaxy nucleus of 9.2″E and 126.4″N (Li et al. 2008) was deprojected for the PA (83.6°) and inclination (53°) of the host galaxy as given by HyperLEDA. The offset corresponds to a radial distance of 3.47′ from the nucleus, at which the oxygen abundance was determined to be about $12 + \log(\mathrm{O/H}) = 8.2 \pm 0.1$. Following Smartt et al. (2008) we therefore adopt an LMC metallicity (Z = 0.008) when estimating an initial mass for the progenitor.

Knowledge of the extinction towards the progenitor is important for the accurate determination of the intrinsic colour, temperature and luminosity. The foreground Galactic reddening given by Schlegel et al. (1998) is $E(B-V) = 0.019$ and there appears to be no clear evidence that the SN suffers from high extinction. Morrell & Stritzinger (2008) suggest the spectrum of SN 2008bk taken on 2008 Apr 12.4 is similar to SN 1999em (with $A_V = 0.31 \pm 0.14$, Baron et al. 2000, Smartt et al. 2003) at +36 days after explosion. An additional handle on the total (Galactic+internal) extinction can be provided by determining the Balmer decrement for nearby H II regions. The closest H II region for which a previous spectroscopic study is available is for W13 (McCall et al. 1985), located 1.5′ from the site of SN 2008hk. McCall et al. (1985) provide raw flux measurements of the Balmer lines for W13 which, assuming an intrinsic flux ratio $H\alpha/H\beta$ of 2.85 (Hummer & Storey 1987), implies $c(H\beta) = 0.67$. For a Cardelli et al. (1989) $R_V = 3.1$ Galactic extinction law this implies a total extinction of $A_V = 1.4$. While this estimate is clearly not directly applicable to the line of sight to SN 2008bk, it indicates that typical starforming regions in the vicinity of SN 2008bk's environment show significant extinction.

We have used the intrinsic colours of LMC and Galactic red supergiants of Elias et al. (1985) to fit the observed *BVIJHK* spectral energy distribution of the progenitor. We find that a late-type M4I supergiant SED can be fit (within the uncertainties) to the observed data with $A_V = 1$ and Cardelli et al. (1989) extinction law (Fig. 2). The brighter *K*-band magnitude of the progenitor could be a suggestion that one (or more) unresolved sources make up the stellar PSF. This is also indicated by the slight elongation of the K-band pre-explosion source (see Fig. 1) and the fact that a faint residual source was left after subtracting the PSF (see Sect. 2.3). However,

[8] http://leda.univ-lyon1.fr/

we note that this slight discrepancy could also be due to colour differences between the standard colours and our 2MASS-like estimate. In Fig. 2 we also show that we cannot definitely rule out an earlier spectral type with higher A_V, as we can equally well fit the observed SED with an M0I spectrum and $A_V = 3$. Indeed one can fit even earlier types (∼G-type yellow supergiants) by invoking A_V values up to 7. However, we favour the M4I solution with Av = 1 as a much higher extinction is not supported by the early SN spectra. While the SN peak light could have evaporated circumstellar dust nearby to the SN (e.g., Dwek 1983) therefore explaining a lower extinction towards the SN than for the progenitor we do not find this very likely in the case of SN 2008bk. While the evaporation of a significant amount of circumstellar dust was observed in the case of SN 2008S (Prieto et al. 2008), there is observational evidence for a significant dusty CSM in only one type II-P event, the highly reddened SN 2002hh (Pozzo et al. 2006; Meikle et al. 2006). Furthermore, in the case of SN 2002hh the dusty CSM was found to lie well outside the dust evaporation radius resulting from an episodic mass loss that ceased ∼30 000 years before the SN explosion (Meikle et al. 2006).

The distance of 3.9±0.4 Mpc and $A_V = 1.0 \pm 0.5$ results in M_K = -9.73 ±0.26 for the progenitor. Levesque et al. (2006) show that using M_K to determine M_{bol} is preferable to using the optical bands. The best fit SED of around M4I would correspond to $T_{eff} \simeq 3500^{+150}_{-50}$K and a bolometric correction $BC_K = +2.9 \pm 0.1$ (both from the Levesque et al. scale). This results in $logL/L_\odot = 4.63 \pm 0.1$ (assuming $M_{\odot,bol} = 4.74$). The position of the star on a HR diagram is shown in Fig. 2, compared with model tracks from the Cambridge stellar evolutionary code, STARS (Eggleton 1971; Pols et al. 1995; Eldridge & Tout 2004). This yields an initial mass estimate of 8.5 ± 1.0 $M_\odot$ for the progenitor. Using the method of Smartt et al. (2008) allowing the core-collapse to take place anytime after the end of He-burning gives an initial mass of 9^{+4}_{-1} $M_\odot$ consistent with the above estimate but with a larger error. We note that adopting $A_V = 3$ and an M0I spectral type would correspond to $T_{eff} = 3750 \pm 100$ K and $logL/L_\odot = 4.8 \pm 0.1$, which would suggest a mass of $11 \pm 2 M_\odot$ for the progenitor. If the K-band PSF magnitude is an overestimate due to blending, then the mass will be lower than we determined. Hence our conclusion that this progenitor is another, moderate mass red supergiant is unlikely to be affected. Although the cool surface temperature of the source is also consistent with models of super-AGB stars (e.g. Eldridge, Mattila & Smartt 2007), its luminosity is lower than would be expected for such a star.

The two best constrained progenitors for type II-P SNe before SN 2008bk were for SNe 2003gd and 2005cs. The progenitor for SN 2003gd was found to be a red supergiant with a spectral type in the range of K5 to M3Ib and an initial mass of 8^{+4}_{-2} $M_\odot$ (Smartt et al. 2004; Van Dyk, Li & Filippenko 2003). The progenitor for SN 2005cs was found to be a red supergiant no hotter than a K5Ia type (Li et al. 2006; Maund, Smartt & Danziger 2005) and have an initial mass between 6 and 8 $M_\odot$ (Eldridge, Mattila & Smartt 2007).

4. CONCLUSIONS

We have identified a source coincident with SN 2008bk in pre-explosion VLT images in four different optical and near-IR bands making use of adaptive optics K_s-band images of the SN from VLT. The colours and luminosity of the pre-explosion source are consistent with it being a red supergiant having an initial mass of 8.5±1.0 $M_\odot$. The coincidence of the pre-explosion source with SN 2008bk makes it the fourth intermediate mass (∼8 $M_\odot$) red supergiant progenitor for a type II-P SN directly detected in pre-explosion images. Our observations also demonstrate the potential of 8m-class telescopes equipped with adaptive optics (see also Gal-Yam et al. 2005, Crockett et al. 2008) in precisely identifying SN progenitors in pre-explosion images.

We acknowledge funding from the EURYI scheme (SJS) and the Academy of Finland project 8120503 (SM). This paper is based on observations collected at the European Southern Observatory, Paranal, Chile. We thank the referee and A. Pastorello for useful comments and the ESO staff for carrying-out the service observations.

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